Implications of a Purely Right-handed b-decay Coupling

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Abstract

We examine the implications of the hypothesis that the decays of the bottom quark occur via pure right-handed couplings . We show that the existing lower limits on the lifetimes for neutrinoless double beta decay severely restrict the neutrino sector of the model and would be satisfied in a natural manner if there is either an $L_e - L_\mu$ or an $L_e - L_\tau$ symmetry in the model. We then show that the cosmological mass density constraints in combination with SN1987A observations imply lower bounds on the masses of the right-handed neutrinos of about 100 MeV (about 65 MeV if there are Goldstone bosons coupling to ν_R's) and also imply that the case of $L_e - L_\mu$ symmetry is inconsistent with data unless there are flavor-changing neutral currents involving the right-handed neutrinos.

It has recently been suggested by Gronau and Wakaizumi[1] that unlike the quarks of the first two generations, the decays of the bottom (b) quark occur purely via its right-handed couplings. In such models, the smallness of the b to c coupling is attributed not to a small value of the corresponding entry in the CKM matrix, V_{cb} but rather to the smaller effective right-handed Fermi coupling constant, G_F^R compared to the usual left-handed Fermi coupling constant, G_F^L. Implementation of this hypothesis within the framework of the left-right symmetric models of weak interactions [2] requires (i) that the left-handed quark mixing matrix be completely different from the right-handed one; and (ii) that the right-handed W-bosons, W_R be rather light such that

$$ G_F^R/G_F^L \simeq \frac{1}{\sqrt{2}} \left(\frac{g_R^2}{M_{W_R}^2} \right) / \left(\frac{g_L^2}{M_{W_L}^2} \right) \equiv \left(\frac{\beta_g}{\sqrt{2}} \right) \simeq V_{bc} \simeq 0.04 \tag{1} $$

In eq.(1), the factor $\frac{1}{\sqrt{2}}$ is the maximal mixing angle between the second and thirs generation in the right-handed charged currents. Despite the overwhelming overall success of the standard $SU(2)_L \times U(1)_Y$ model, it has been shown that all B-decays, rare processes, $B - \bar{B}$ mixing and CP-violation pattern can be reproduced in this model without excessive fine tuning[1] of parameters. Future special purpose experiments measuring Λ_b polarization via its weak decays[3] will directly settle this issue.

In this note, we would like to point out that considerations of the neutrino sector , briefly alluded to already in the original paper[1], very strongly constrain this model. As noted there, the low value for the M_{W_R} requires that neutrinos must be Majorana fermions. In particular to be consistent with the results of experiments searching for right-handed currents in muon and beta decay[4] the right-handed neutrinos of the electron and muon generation must be heavier than 7 MeV or so. On the other hand, the fact that in this model, all semileptonic decays of the b-quark must proceed dominantly via the emission of right-handed neutrinos implies an experimental upper limit on the $m_{\nu_{iR}}$ $(i = e, \mu)$[5] [3].

$$ m_{\nu_{iR}} \leq 1 \ GeV \tag{2} $$

Note that this is very different from the conventional left-right models with the see-saw mechanism where $m_{\nu_R} \approx M_{W_R}$[6] and as a result ν_R essentially decouples from the low energy effective theory. In the model of ref.[1], the ν_R's are very much a part of low energy world and will effect the low energy observations.

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[3] In ref.[1], a stricter upper limit of about 200 MeV has been used.

The first low energy process we analyze is the neutrinoless double beta decay . We show that present limits on the lifetimes for neutrinoless double beta decay[7] can be satisfied in the model only if there is extreme fine tuning in the ν_R sector of the theory or if there is an exact $L_e - L_\mu$ or $L_e - L_\tau$ symmetry in the theory.

We then discuss the constraints from cosmology on this model. Since the right-handed neutrinos in this model are in the moderate mass range of less than a GeV, their relic density can violate the bounds from cosmological energy density[8] as well as the structure formation[9] unless they decay fast enough. Therefore any model apart from satisfying the bounds from $\beta\beta 0\nu$ lifetimes, must also provide a mechanism for fast decay of the right-handed neutrinos . Using these constraints in combination with the ones arising from SN1987A observations on the decay mode $\nu_R \to e^+ e^- \nu_L$, we show that there must be a lower bound of 100 MeV on the mass of the right-handed neutrinos, if they do not couple to any Goldstone bosons and 66 MeV if they do. In particular, we show that that the existing ALEPH data[10] which observed the decay of the b-hadrons to tau leptons rules out the first possibility (i.e. $L_e - L_\mu$ symmetry) in the context of left-right models (without Goldstone bosons) provided there are no flavor-changing neutral currents involving the right-handed neutrinos.

I. Minimal left-right model for pure right-handed b-decay:

The minimal left-right gauge model that leads to a pure right-handed b-decay couplings is a slightly extended version of the model discussed in ref.[6] . The neutrinos in the model of ref.[6] are Majorana particles and the mass matrix involving the left and the right-handed neutrinos have the see-saw form which for natural values of parameters leads to $m_{\nu_R} \approx M_{W_R}$ so that ν_R decouples from the low energy physics. Since in the model under discussion, the ν_R's play a key role in the b-decays, the parameters of the see-saw matrix have to be fine-tuned such that the right-handed neutrinos lighter than 1 GeV. Secondly, the model of ref.[6] due to the constraint of parity symmetry can lead to symmetric quark and lepton mass matrices (in the case that CP-violation is spontaneous) and this leads to identical quark mixings in the left and right-handed charged currents. We have to make sure that is not obeyed by the pure right-handed b-decay model.

We denote the lepton fields by $\Psi_a \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_a$, and the quark fields by $Q_a \equiv \begin{pmatrix} u \\ d \end{pmatrix}_a$, where $a = 1, 2, 3$. Under the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$,

they transform as $\Psi_{a\,L} \equiv (1/2,\ 0,\ -1)$ and $\Psi_{a\,R} \equiv (0,\ 1/2,\ -1)$ and similarly for the quarks with the appropriate $B - L$ quantum number. The Higgs sector of the model consists of the bi-doublet field $\phi \equiv (1/2,\ 1/2,\ 0)$ and triplet Higgs fields: $\Delta_L(1,\ 0,\ +2) \oplus \Delta_R(0,\ 1,\ +2)$. The Lagrangian for this model is given in ref.[6]. The gauge symmetry is spontaneously broken by the vacuum expectation values:$< \Delta_R^0 > = V_R$; , $< \Delta_L^0 > = 0$; and $diag.< \phi > = (\kappa, \kappa')$. As usual, $< \phi >$ gives masses to the charged fermions and Dirac masses to the neutrinos whereas $< \Delta_R^0 >$ breaks the $SU(2)_R$ symmetry and gives Majorana mass to the right-handed neutrinos.

The charged current weak interaction Lagrangian in this model has the following general form:

$$L_{wk} = \frac{g_L}{\sqrt{2}} \left(\bar{P}_L \gamma_\mu V_L N_L + \bar{\nu}_L \gamma_\mu U_L E_L \right) W_L^\mu$$

$$+ \frac{g_R}{\sqrt{2}} \left(\bar{P}_R \gamma_\mu V_R N_R + \bar{\nu}_R \gamma_\mu U_R E_R \right) W_R^\mu$$

$$+ \zeta_g M_{W_R}^2 W_L^+ W_R^- + h.c. \tag{3}$$

In eq.(3), $P \equiv (u, c, t);\ N \equiv (d, s, b);\ \nu \equiv (\nu_e, \nu_\mu, \nu_\tau)$ and $E \equiv (e, \mu, \tau)$. The $V_{L,R}$ and $U_{L,R}$ denote the weak mixing matrices in the quark and lepton sectors respectively. In order to have $V_L \neq V_R$, we must have either hard CP-violation with the vev's of the bidoublet fields complex or we can have spontaneous CP-violation with two bi-doublet fields[11]. The gauge mixing parameter ζ_g is bounded by $K \to 3\pi$ decay to be less than 0.01.

The right-handed b-decay model is characterised by the following V_L and V_R[1]:

$$V_L = \begin{pmatrix} cos\theta_c & sin\theta_c & 0 \\ -sin\theta_c & cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix};\ V_R \simeq \begin{pmatrix} 1 & -s & s \\ \frac{s^3}{2\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -s\sqrt{2} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{4}$$

We have ignored the CP-violating phase in V_R. Eq.(4) implies that the b-quark decays via the right-handed currents. Here, θ_c is the Cabibbo angle and the parameter $s = |V_{ub}/V_{cb}|\sqrt{2} \simeq 0.08 \pm 0.03$. After the fermion mass matrices are diagonalized, the model will lead to the weak interaction Lagrangian of eq.(3). There are no Goldstone bosons in the model. We will also assume that all left-handed neutrinos are Majorana particles and have masses in the electron-volt range so that they are consistent with the laboratory upper limits as well as the cosmological constraints.

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II. Bounds from neutrinoless double beta decay:

Let us now consider the implications of the present limits on the lifetimes for neutrinoless double beta decay[7] for this model.There are several contributions to $\beta\beta0\nu$ in this model: (i) left-handed ν exchange; (ii) right-handed ν_R exchange; (iii) $\nu_L - \nu_R$ mixing and (iv) Δ_R^{++} exchange. The contributions (i) and (iv) can be adjusted to obey the experimental limits without effecting the main idea of the model. Therefore , we focus on the right-handed neutrinos and the $\nu_L - \nu_R$ mixings. As already noted in ref.[1], the $\nu_{e,\mu R}$ must have masses above 7 MeV in order to be consistent with weak decay data. Our main observation in this paper is that since they are Majorana fermions and since the W_R mass is low, their contribution to neutrinoless double beta decay is non-negligible. In fact, if we write the rate for $\beta\beta0\nu$ decay process for a nucleus such as ^{76}Ge as:

$$\Gamma(\beta\beta0\nu) \simeq \frac{G_F^4 Q^5}{60\pi^3}|A|^2 \tag{5}$$

A will be given by[12]:

$$|A| \simeq \frac{\omega_0 p_F E_F \beta_g^2}{4\pi^3}\Sigma_i U_{Rei}^2 m_{\nu_{iR}} \qquad (for \quad m_{\nu_{iR}} \ll E_F \ll p_F) \tag{6a}$$

and

$$|A| \simeq \frac{\omega_0 E_F p_F^3 \beta_g^2}{12\pi^3}\Sigma_i \frac{U_{Rei}^2}{m_{\nu_{iR}}} \qquad (for \quad E_F \ll p_F \ll m_{\nu_{iR}}) \tag{6b}$$

In eq.(6), p_F and E_F denote the Fermi Momentum and Fermi energy of the nucleons in the decaying nucleus ; $p_F \approx 100 MeV$ and $E_F \approx 5\ MeV$ for typical nuclei of interest. Therefore, the first equation eq.(6a) applies when the relevant ν_R lighter than 100 MeV and the eq.(6b) applies when in the opposite case. In ref.[12], the parameter ω_0 was estimated from two neutrino double beta decay to be about $4\ MeV^{-1}$, which we use here. The present neutrinoless double beta decay experiments[7] imply the following bounds on the parameters of the model:

Case(a):

$$\beta_g^2\Sigma_i U_{Rei}^2 m_{\nu_{iR}} \leq 2\ eV \quad for\ 7\ MeV \leq\ m_{\nu_R} \leq 10\ MeV \tag{7a}$$

Case(b):

$$\beta_g^2\Sigma_i \frac{U_{Rei}^2 p_F^2}{3m_{\nu_{iR}}} \leq 2\ eV \quad for\ .1\ GeV \leq m_{\nu_R} \leq\ 1\ GeV \tag{7b}$$

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According to eq.(1), the parameter $\beta_g \simeq .055$ and the inequalities (7a) and (7b) are violated by four orders of magnitude, if we do not assume any fine tuning among the parameters in the sum. In the intermediate region of $10\ MeV \leq m_{\nu_R} \leq 100\ MeV$, we expect a similar conclusion to hold.(We have used the fact that the semi-leptonic decays of the b-quark require the mixing angle $U_{Ree} \simeq 1$). This leads us to conclude that *the only way to make the right-handed b-decay model consistent with limits from $\beta\beta 0\nu$ is to demand severe fine tuning in the right-handed neutrino sector so that in case(a), $\Sigma_i U^2_{Rei} m_{\nu_{iR}} \leq keV$ and a similar strong cancellation for the heavy ν_R case (b).*

One way to achieve this cancellation is to have an exact $L_e - L_\mu$ or $L_e - L_\tau$ symmetry in the theory so that the neutrino less double beta decay is forbidden by the symmetry.

III. Cosmological constraints:

Let us now turn to the discussion of the cosmological constraints on the model. In order to see how the heavy right-handed neutrinos can avoid the cosmological mass density constraints, let us first consider the effects of annihilation in the early universe. Since the W_R and Z' are only a few times heavier than the usual W's and Z's, the discussion of Lee and Weinberg[14] for relic abundance of heavy neutrinos can be carried over with small modifications and one must require $m_{\nu_R} \geq 6\ GeV$ in order to satisfy the mass density constraints. Since semileptonic b-decays to all three leptons have been observed, the right-handed neutrinos cannot satisfy this bound. We must therefore find a mechanism for the right-handed neutrinos to decay fast enough in the model. Since the ν_R's decouple in the early universe when they are non-relativistic, their masses and lifetimes must satisfy the constraint[8]:

$$\frac{1}{\beta_g'^2} \left(\frac{1\ GeV}{M_{\nu_{iR}}} \right)^2 \left(\frac{\tau_{\nu_R}}{t_U} \right)^{\frac{1}{2}} \leq .05 h^2 \tag{8}$$

Here, h is the Hubble constant in units of $100\ km\ sec.^{-1}(Mpc)^{-1}$. In eq.(8), $\beta_g' \equiv (g_R^2 M_Z^2 / g_L^2 M_{Z'}^2)$ since the ν_R annihilation takes place via the exchange of the heavier Z' in the model. In the minimal left-right model described above, we have the relation that $M_{Z'}^2 \simeq 3 M_{W_R}^2$[6] leading to $\beta_g' \approx .42 \beta_g$.

$L_e - L_\mu$ *symmetry:*

To see the implications of eq.(8) for the ν_R spectrum, let us first consider the model with an $L_e - L_\mu$ symmetry. Due to the $L_e - L_\mu$ symmetry of the model, the

$\nu_{\mu R}$ and the ν_{eR} are degenerate and and their decay can occur either via pure W_R exchange or via $W_R - W_L$ mixing leading to the following final states:

$\underline{W_L - W_R \text{ mixing induced decays:}}$

(a): $\nu_{e,\mu R} \to e^+ e^- \nu_e$ for $m_{\nu_R} \leq 108 \ MeV$

(b): $\nu_{e,\mu R} \to e^- \mu^+ \nu_\mu$ for $108 \ MeV \leq m_{\nu_R} \leq 140 \ MeV$;

(c): $\nu_{e,\mu R} \to e^\pm \pi, \ e^\pm \ hadrons$ for $m_{\nu_R} \geq 140$ MeV.

$\underline{W_R \text{ induced decays:}}$

In this case, if m_{ν_R} is less than 140 MeV or so, there are no kinematically allowed decay modes; as a result, the ν_R stable. But, it is more massive than 140 MeV, the hadronic decay modes open up so that ν_R becomes unstable.

From eq.(8) and the the decay rate $\tau_{\nu_R}^{-1} \simeq G_F^2 \zeta_g^2 m_{\nu_R}^5/(192\pi^3)$ we find that $m_{\nu_{eR}} \geq 30$ MeV for $\zeta_g \leq .01$. However, we will show in a subsequent section that there are very strong bounds on the $\nu_R \to e^+ e^- \nu_e$ mode from lack of observation of gamma rays by the SMM during SN1987A [15] , which help to push the lower bound to 100 MeV. For the choice of parameters of the model, the other cases all satisfy the constraint in eq.(8) so that the lower bounds respectively are 110 MeV for the case of $\zeta_g \neq 0$ and 140-150 MeV otherwise.

Coming now to the $\nu_{\tau R}$ decay, it can occur via three different mechanisms;(i) the flavor changing neutral current (FCNC) interactions induced via the see-saw form for the neutrino masses; (ii) the $W_L - W_R$ mixing and (iii) via W_R exchange. In the FCNC mechanism, the typical strength of the interaction is $\approx G_F \times \zeta_\nu$; for $m_{\nu_{\tau R}} \leq 140$ MeV, the final state is $e^+ e^- \nu_{\tau L}$; otherwise, the single pion and other final states open up. Using eq.(8), and an analogous decay rate formula, we get:

$$\left(\frac{m_{\nu_{\tau R}}}{1 \ GeV}\right)^9 \zeta_\nu^2 \geq .72 \times 10^{-18} \tag{9}$$

One can obtain a plausible estimate for ζ_ν from the see-saw formula for neutrinos to be: $\zeta_\nu^2 \approx m_{\nu_{\tau L}}/m_{\nu_{\tau R}} \approx 10^{-3}$. Eq.(9) then implies that for this mechanism to produce a decay fast enough for cosmology, we must have $m_{\nu_\tau R} \geq 45 \ MeV$ or so. But again , since the only final state here is the $e^+ e^- \nu_\tau$, SN1987A bounds will apply and the lower limit on $m_{\nu_{\tau R}}$ will become 100 MeV or so.

On the other hand, if $W_L - W_R$ mixing or W_R exchange provide the dominant decay mechanism, then the only allowed final state involves a τ lepton and therefore, we must have $m_{\nu_\tau} \geq 2$ GeV or so for this decay to be kinematically allowed. This is however inconsistent with data[5] on semileptonic decays ruling out $L_e - L_\mu$ symmetry as a way to satisfy the $\beta\beta 0\nu$ constraints.

$L_e - L_\tau$ symmetry:

For the case with $L_e - L_\tau$ symmetry, we have ν_{eR} and $\nu_{\tau R}$ degenerate. So, the ν_{eR} (or $\nu_{\tau R}$) can decay as in the previous case and the bounds cited above apply. As for the ν_μ, it can decay either via the FCNC mechanism in an analogous manner to the above or via the $W_L - W_R$ mixing or the W_R exchange. In first case, the most stringent lower bound will arise from SN1987A gamma ray observations. In the other cases, since a muon must be produced in the final state, the bound increases to 110 MeV or so.

IV. Bounds from supernova cooling:

Finally, we briefly comment on the constraints on the model from supernova cooling. In the usual scenario[16] for supernova cooling, the 1-10 sec. cooling period of the hot collapsed core is via ν_{iL} emission. Observation of the neutrino burst from the supernova SN1987A[17] confirm this idea. A simple minded way to understand this is to note that the effective mean free path of a typical neutrino (with $E_\nu \simeq$ 30 MeV) is given by $\lambda_\nu \simeq \left(n_T \sigma_\nu^{eff}\right)^{-1} \approx (n_T G_F^2 E_\nu^2)^{-1}$. If we use $n_T \approx 10^{39}$ corresponding to a core density $\rho_c \approx 10^{15} gr.(cm)^{-3}$, then we get $\lambda_\nu \approx 30$ cm. In the random walk approximation, the total diffusive path length is given by $\ell_{tot} = \frac{R^2}{\lambda_\nu} \approx$ $3 \times 10^8 meters$ for $R \approx 10$ km. Since the neutrinos travel with the velocity of light, this implies that the neutrinos escape the supernova in about a second ; this gives the cooling time $\Delta t \simeq 1$ $sec..$

In the present scenario, the production of right-handed neutrinos in the supernova core takes place via the following mechanisms[18] : (i) $e_R + p \rightarrow n + \nu_R$; (ii)$e_R^+ + n \rightarrow p + \nu_R$ and (iii) $e^+ e^- \rightarrow \nu_R \nu_R$. These production rates as well as other interaction rates for the ν_R's are smaller than those for the left-handed neutrinos due to higher mass for the W_R's . For $M_{W_R} \approx 5 \times M_{W_L}$, the mean free path for the ν_R's is longer by a factor of roughly ≈ 600 . This implies that the time required per collision is $\lambda_{\nu_R}/c \approx 10^{-6} sec$. As a rseult, the ν_R's formed travel out of the core much faster than the ν_L's. Thus the energy loss via ν_R diffusion can be thought of qualitatively as a two step process- (i) formation on a short distance scale due to electron mean free path being small and (ii) diffusion of the ν_R over a much further distance before a recapture- this distance being about 600 times the corresponding ν_L travel path. Repeating this process, leads to the ν_R cooling mechanism with an effective time scale for this is of order:

$$\Delta t_R^e \approx \Delta t_L \left(\frac{\lambda_\nu}{\lambda_{\nu_R}}\right) \leq 10^{-3} sec. \tag{10}$$

For the $\nu_{\mu,\tau R}$ cases, there are only Z' contributions and therefore the corresponding Δt_R is of order 10^{-4} sec. These qualitative considerations make it clear that ν_R cooling is much more efficient contrary to observation. Clearly if $m_{\nu_R} \geq 35$ MeV or so, this additional cooling mechanism will be Boltzman suppressed. Let us note that, this bound is much less stringent than the ones derived earlier.

V. Bounds on the $e^+e^-\nu_L$ decay mode from γ-ray data from SN1987A:

We saw in sec.III that there are several situations where the ν_R can decay to $e^+e^-\nu_L$ final states and that for allowed ranges of parameters in the theory, the cosmological mass density constraints allow a lower bound in the range of 30 to 55 MeV. In this section, we will show that in these cases, lack of any evidence for γ-rays in the MeV range from the Solar Maximum Mission[19] implies a more stringent lower bound. First note that for supernova emission rate for heavier right-handed neutrinos is suppressed by the Boltzman factor $e^{-\frac{m_{\nu_R}}{kT}}$. If the only (or dominant) decay mode for ν_R involves the e^+e^- final state, then these final state products can lead to gamma rays either via bremstrahlung or annihilation. The details of this were discussed in ref.[15], where it was shown that if a heavy neutrino lives longer than about 100 sec. and it decays to either $e^+e^-\nu_L$ or $e^+e^-\nu_L\gamma$, then there will be an observable photon flux near the earth. For us the relevant gamma-ray production mechanism is the radiative decay$\nu_R \rightarrow e^+e^-\nu_L\gamma$. The local photon flux due to this mechanism was estimated in the first reference of [15] to be:

$$\Phi_\gamma \simeq \frac{\alpha N_{\nu_R} B}{8\pi^2 D^2 \Delta t} \tag{11}$$

In the above equation, N_{ν_R} stands for the number of ν_R's emitted from the supernova; B denotes the branching ratio for the decay mode $\nu_R \rightarrow e^+e^-\nu_L$ and Δt denotes the duration of neutrino emission in the supernova (taken to be 10 sec. below); D is the distance from SN1987A to the earth. Experimentally, $\Phi_\gamma \leq 0.1\ cm^{-2}sec^{-1}$.. We will assume that the entire suppression in the gamma ray signal is due to the Boltzman suppression of the emission intensity of ν_R. We have two sources for this suppression: (i) one is the Boltzman suppression factor for the higher mass and (ii)the other arises from the fact that for the parameters of our model, the typical lifetimes for ν_R are about 5-10 sec. Combining them, we get (for $B = 1$),

$$\left(\frac{m_{\nu_R}}{kT}\right)^{\frac{3}{2}} e^{-\frac{m_{\nu_R}}{kT}} e^{-\frac{t}{\tau}} \leq 10^{-10}/(m_{\nu_R}\ in\ MeV) \tag{12}$$

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Assuming the temperature of the emitted ν_R's to be higher than 5 MeV, $t = 100\ sec.$, $\tau = 10\ sec.$, we get $m_{\nu_R} \geq 100$ MeV.

The lower bound derived in eq.(12) clearly deteriorates as τ_{ν_R} becomes much shorter than 100 sec. However, it is possible to derive a bound which is valid as long as $\tau_{\nu_R} \geq 10^{-3}\ sec.$ (which is the time required for ν_R to escape the core).

Let us assume that $\tau_{\nu_R} \leq 100\ sec.$ so that the majority of the ν_{iR}'s decay inside the progenitor of SN1987A. This decay, if it involves e^+e^- final states will deposite inside the mantle of magnitude $\approx W_{\nu_R}$, the total energy carried by the ν_R's. W_{ν_R} is suppressed by the Boltzman factor but is enhanced by the larger core escape efficiency of the ν_R's; so we estimate:

$$W_{\nu_R} \approx (\frac{m_{\nu_R}}{T})^{\frac{3}{2}} e^{-\frac{m_{\nu_R}}{T}} \times (\frac{\Delta t_{\nu_L}}{\Delta t_{\nu_R}}) W_{\nu_L} \tag{13}$$

W_{ν_L} is the total ν_L luminosity. Demanding that the energy deposited will not exceed the total mantle (explosion)energy $\approx 10^{51}\ ergs \approx 10^{-2} W_{\nu_L}$ implies that:

$$(\frac{m_{\nu_R}}{T})^{\frac{3}{2}} e^{-\frac{m_{\nu_R}}{T}} \leq 10^{-5} - 10^{-6} \tag{14}$$

For $T_{\nu_R} \approx 5$ MeV, we get from eq.(14), $m_{\nu_R} \geq 75 - 90$ MeV.

Note that the above considerations referring only to the total energy deposition are very conservative.In the conventional mechanism the above 10^{51} erg energy is transferred to the mantle via the shock wave and takes several hours to reach the stellar surface resulting in the observed several hour delay between the time of the neutrino pulse and the supernova explosion. In the case of the ν_R decay, the time of energy depostion is of order of 100 sec rather than a few hours. Although without a detailed modelling of the supernova, it is hard to say precisely how much this will improve the bound , it is none-the-less clear that it would imply the right hand side of eq.(14) to be even less and will lead to stronger bounds on ν_R masses.

VI. Goldstone boson coupling to right-handed neutrinos:

Next, let us consider the possibility that the right-handed neutrinos decay via their couplings to a Goldstone boson invoked in ref.[1] for the purpose of allowing faster two-body decays in order to avoid cosmological constraints. The detailed gauge model in this case will have to be more elaborate than the one mentioned (e.g. ref.[20] as one possibility). It appears however that, one can still draw similar lower bound on the right-handed neutrinos in this case in a fairly model independent manner. The constraints arise from the interplay between the cosmological

constraint in eq.(8) and the requirement that the coupling of any Goldstone boson to electrons must have a strength less $\leq 10^{-12}$ in order to satisfy the constraints from the cooling of red giants[21] . Denoting the $\nu_R \rightarrow \nu_L + \chi$ (where χ is the massless Goldstone boson) coupling by $f_{\nu_R \nu_L \chi}$, we get from eq.(8) the following inequality:

$$m_{\nu_R}^5 f_{\nu_R \nu_L \chi}^2 \geq 1.2 \times 10^{-30} \ GeV^5 \tag{15}$$

The value of $f_{\nu_R \nu_L \chi}$ is expected to be of the same order of magnitude as the $ee\chi$ coupling since both of them arise from the same Yukawa interaction in the basic Lagrangian i.e.the $\bar{\psi}_L \phi \psi_R$ term. Therefore, using the astrophysical arguments, we can assume the $f_{\nu_R \nu_L \chi}$ to be also $\approx 10^{-12}$. Then , in order to satisfy eq.(8), we need $m_{\nu_R} \geq 66$ MeV .

In conclusion, we have pointed out that in the model for pure right-handed b-quark decay model, constraints of neutrinoless double beta decay and cosmology require that there must either be an $L_e - L_\mu$ or $L_e - L_\tau$ symmetry in the model. Furthermore, if there are no flavor changing neutral current interactions involving the right-handed neutrino in the model, then only symmetry that works is the $L_e - L_\tau$. In either of the cases , we find that cosmology and SN1987A observations imply lower bounds on the right-handed neutrino masses which are significantly higher than the 7 MeV value used in ref.[1]. We summariza these bounds for various cases in table I. Future high precision measurements of the semileptonic $B \rightarrow D^* \ell \nu_R$ decays sensitive to neutrino masses in the range of 100 MeV will provide decisive tests of this model. In any case, if we combine our lower bounds with the upper bound of 200 MeV used in ref.[1], the allowed window for the model gets considerably narrowed.

Acknowledgement

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Table I

Particle	Symmetry	Decay mechanism	final state	$(m_{\nu_R})_{min}$	Source
$\nu_{e,\mu R}$	$L_e - L_\mu$	$W_L - W_R$ mixing	$e^+e^-\nu_L$	100 MeV	SN1987A
$\nu_{\tau R}$	"	$\nu_L - \nu_R$ mixing	"	100 MeV	SN1987A
$\nu_{\tau R}$	"	$W_L - W_R$ mixing or W_R exchange	$\tau + X$	2 GeV	cosmology
$\nu_{e,\tau R}$	$L_e - L_\tau$	$W_L - W_R$ mixing	$e^+e^-\nu_L$	100 MeV	SN1987A
$\nu_{e,\tau R}$	"	W_R exchange	$e\pi$	140 MeV	cosmology
$\nu_{\mu R}$	"	$W_L - W_R$ mixing	$\mu + X$	110 MeV	cosmology
$\nu_{\mu R}$	"	$\nu_L - \nu_R$ mixing	$e^+e^-\nu_L$	100 MeV	SN1987A
all ν_R	any	$\nu_R \rightarrow \nu_L + \chi$	$\nu_L + \chi$	66 MeV	cosmology

Table caption: The table summarizes the lower bounds on the different ν_R's for various cases.